May 1999

CFIC, Inc.
Resonant Power: Technology & Market Summary

1. Overview

CFIC, Inc. has developed a technology base in advanced resonant thermal-to-electrical energy systems and is in the process of commercializing these technologies for a variety of promising market segments. Thermal energy sources include both fossil and renewable (solar, biomass). Reversed systems (electric-to-thermal) provide electrically-driven heat-pumping and refrigeration devices.

CFIC was founded in 1989 to provide innovative product and process development solutions for manufacturers. The principals brought with them decades of experience in advanced energy conversion systems to offer leading-edge technology support in mechanical design, materials, controls and systems integration. While providing contract development services, CFIC also pursued free-piston Stirling engine (FPSE) and reciprocating alternator/motor development as internally funded research.

In 1991, a subsidiary of the Cummins Engine Co. asked CFIC to join them in the development of a new DOE sponsored solar power system that combined reflective dishes with advanced CFIC-designed FPSEs driving reciprocating alternators. Sandia National Labs were also actively involved in this program. CFIC started development testing of a 5 kW FPSE/alternator package in late 1993 and eventually accumulated more than a thousand test bench hours. On-sun operation was successfully initiated in May, 1995.

Cummins elected to exit the solar energy business in 1996, but CFIC, building on its working relationships with Sandia and Los Alamos National Labs, launched development and commercialization of the next generation of linear-motion thermal conversion technology, replacing FPSEs. We have initially focused product development on four primary market segments:

Linear Compressors for Cryogenics (pulse tube, J-T)

TARGET™ Electric Generation (thermoacoustic solar & fueled co-gen)

Oil-Free Compression and Vacuum Pumps

CFC-free Thermoacoustic Refrigeration Drivers

Two key proprietary technologies are included in the body of knowledge supporting CFIC's commercialization plan:

- **STAR™ Reciprocating Alternator/Motor** provides high-efficiency direct conversion of reciprocating force & motion to AC electric power, or vice versa. STARs are compact, self supporting and cost effective. Their Commuter™ flexing bearings eliminate all rubbing and rolling contacts to provide wear-free operation and unlimited service life with zero lubrication. STARs can be configured in opposing pairs, thus self-balancing all mechanical vibrations. CFIC has built STARs from 0.3 to 15 kW output and with more than 90% efficiency. Production costs in volume are similar to rotary permanent magnet motors of comparable power and production volume.

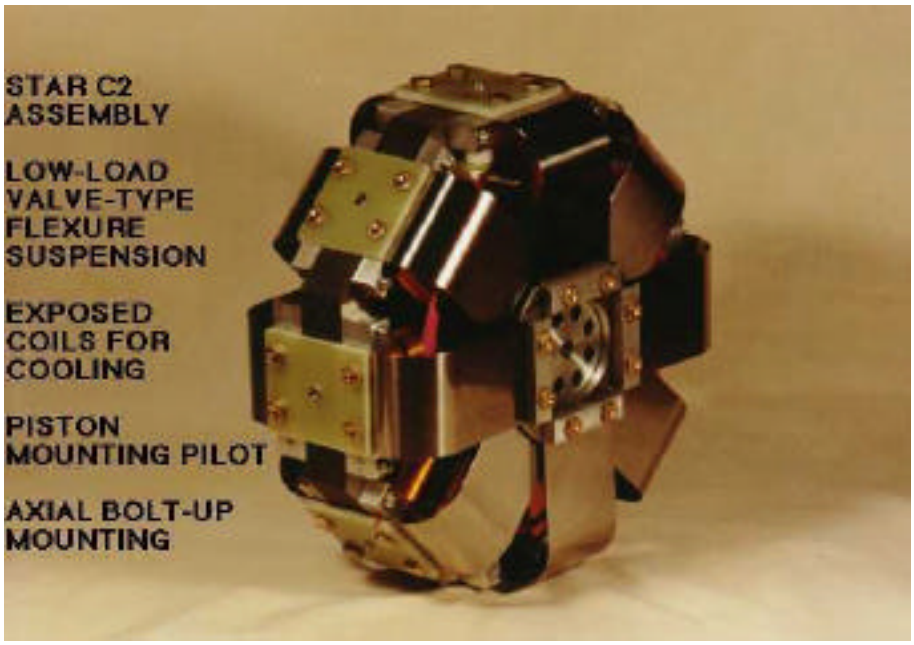


Figure 1: 2kWe STAR™

- **Linear Reciprocating Thermal-to-Mechanical Power Conversion** has been provided by the venerable Stirling engine cycle in numerous R&D projects. CFIC's extensive experience with the free-piston Stirling engine (FPSE) concept has now led beyond the FPSE for industrial and consumer product applications. Following the Cummins/DOE solar project, CFIC has acquired from Los Alamos National Laboratory an exclusive world-wide license for advanced ThermoAcoustic Converters (TACs). TACs provide about the same efficiency as FPSEs, but with no moving parts in a smaller package....thus dramatically lowering cost and greatly improving total system reliability.

Following extensive market analysis, CFIC has identified several promising segments for the commercialization of the STAR and TAC technologies.

2. STAR Linear Compressor Markets

A STAR can be driven by AC electricity to produce efficient mechanical reciprocation for gas compression and pressure wave generation. CFIC has identified three applications where the STAR offers unique product benefits.

2.1 Gas Liquefaction

Cryenco (Denver, CO) is an established manufacturer of vacuum insulated tank trailers for the transport of liquefied gases. Under license from Los Alamos National Laboratory, Cryenco has been developing pulse-tube technology, driven by a thermoacoustic engine and, in smaller units, by a STAR linear reciprocating motor, to provide point of use gas liquefaction capability. Recently, Cryenco was purchased by Chart Industries. This cooperation has now been transferred to PSI, a sister division in Chart. Potential products being evaluated use STARs in a range from 300 watts to 50 kilowatts to produce up to 2000 gallons per day of liquefied natural gas and process gases.

One potential market is the enhancement of natural gas collection and distribution: individual low flow natural gas well-heads (up to 200,000 cubic feet per day) that are too remote or too environmentally sensitive for economical pipeline construction; on-demand wells connected to pipelines; and oil wells with flare gas. A Cryenco tank trailer parked at the well-head would be equipped with this liquefaction unit and will collect and store the LNG for periodic pick-up. The pulse-tube liquefaction process can also be used for efficient, compact LNG refueling stations; supplemental urban natural gas distribution; oxygen enrichment for home medical use; point-of-use production of liquefied process gases; and capturing and re-liquefying lost gas in argon distribution centers.

Since it directly resonates the high pressure helium gas used in the pulse-tube process, without wear and without contact with the natural gas, the STAR linear compressor is the enabling technology. Mechanical drives need a high speed mechanical lubricated seal against the high-pressure helium – no satisfactory long-life seal exists. A 50 kW STAR compressor is about 5 cubic feet in volume and weighs less than 400 pounds. A similar capacity conventional compression system measures 10’x 3’x 3’ (90 cubic feet), weighs about 5000 pounds, and is several times more expensive than the STAR.

CFIC and PSI have initiated STAR license discussions. PSI plans to buy CFIC-built units for their development effort, fund CFIC R&D for any necessary STAR design modifications, buy CFIC-built units for initial low-rate production, and then perhaps phase into their own licensed production.

2.2 Small-Scale Cryogenic Cooling For Telecommunications and Medical Use

In partnership with a leading telecommunications equipment supplier, CFIC developed a 300 W STAR compressor to drive a pulse tube cryogenic cooler, part of a system that significantly enhances the operational range of wireless RF communication systems, such as cellular telephone receivers mounted in towers. This demanding application requires 40,000 hours of continuous operation between major inspections and a fatigue design life of at least 10^{10} cycles. Limited production (100-200 units per month) was scheduled to start in 1998 with a produce-to-cost target of $1500 per STAR compressor unit. While the telecom market for cooled antennas has not matured as expected, CFIC has adapted the 300 watt STAR and joined with Mesoscopic Devices, LLC to provide a turnkey cryocooler for medical oxygen and laboratory uses. The prototype provides approximately 10 watts net cooling at 90K from less than 300 watts input power.

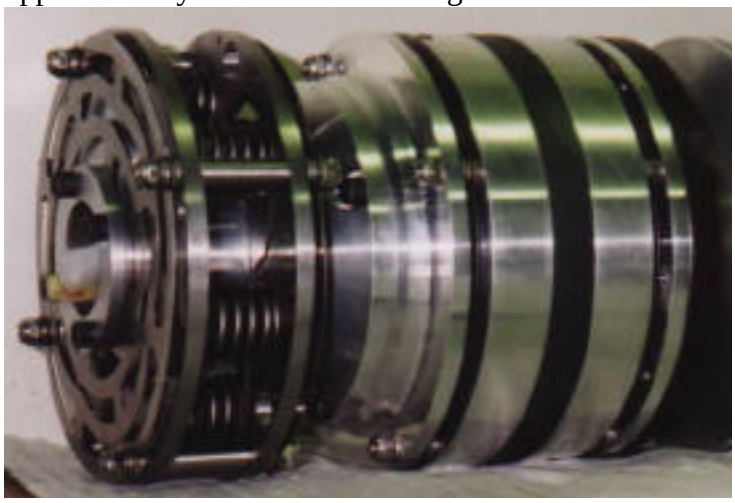


Figure 2: Internal Components of the STAR™ driven Telecom Cryocooler

2.3 Environmentally Friendly Refrigeration

Dr. Steven Garrett (now at the Applied Research Lab of Penn State University) pioneered the use of thermoacoustic technology to create refrigeration cycles which, because they do not involve phase changes in fluids, don't need any CFC or CFC-substitute refrigerants. His first successful field "installation" was on the Space Shuttle Discovery in 1991, which earned him the 1993 Rolex Award for Enterprise.

The US Government has recently funded Dr. Garrett to use the thermoacoustic concept to develop a CFC-free 3 ton air conditioning system. This prototype design is based on a CFIC STAR motor-compressor. A number of interactive development and product application efforts using thermoacoustic cycles are underway and have already resulted in significant cycle efficiency and dynamic stability improvements. It is anticipated that this trend will continue to accelerate, thus making thermoacoustic refrigeration products commercially competitive in the near future (cost, efficiency, reliability) *while* eliminating a significant source of CFC and CFC-substitute (such as HCFC-22) usage that has become an important world-wide environmental issue.

3. TARGET™ Electrical Power Generation Markets

Using the thermal-to-mechanical energy capability of the ThermoAcoustic Converter (TAC) to drive a STAR alternator provides a low cost, technologically advanced package that can meet a number of remote off-grid electrical power and heating market needs.

3.1 Small Scale Combined Heat and Power

CFIC has been working with several European HVAC and gas utility companies (including British Gas and GASTEC) who are actively pursuing the development of new household appliances that would combine gas-fired heat and hot water production with electrical power cogeneration capability. 0.5-5 kilowatts (kW) of electrical power could be produced for household consumption and/or fed into the grid to reduce peaking power demand. Since electrical power would normally only be produced when the gas burner is running to provide heat or hot water, the cogeneration conversion efficiency of burning a little more gas to produce the needed electricity is 3 to 4 times higher than even modern, central utility power generation and distribution systems. Thus, the homeowner's additional gas cost to produce electricity is a fraction of the retail cost of electricity.

Current European market studies have targeted $750-1000 more than today's stand-alone gas-fired heat and hot water systems for the 1-2 kW size class. For the homeowner this offers a payback on his investment within a few years. Regulated utilities can also envision significant benefits since this capital equipment cost is considerably cheaper than the total cost of adding and operating new utility power generation and transmission capacity (normally assessed greater than $1500 per kW).

Based on its European contacts and their product requirements, CFIC believes gas-fired burners can be successfully coupled with ThermoAcoustic Converters (TAC), which convert the thermal energy into reciprocating mechanical energy and drive integral STAR alternators. In cooperation with the Los Alamos National Laboratory, CFIC is now under contract with the New York State Energy Research & Development Authority (NYSERDA) and an European appliance OEM to develop a TAC driving a 0.5-1 kW STAR alternator (called TARGET™). The proof-of-concept prototype testing, completed in May, 1997, demonstrated operational capability and dynamic stability. The first development unit went into test in mid 1998, demonstrating high-speed operation and size required for product usage. We are currently upgrading the manufacturing and performance of the fired heat exchangers in a second generation.

Commercialization of CFIC's TARGET components and integration with gas-fired heating systems is expected to take 18-24 months after full development go-ahead, pending success with the revised prototype. The most critical development challenges are expected to be meeting the system efficiency requirements (20-24%) and reducing the high volume (> 100,000 units per year) production price to about $750 per 1 kW

package. European HVAC OEM licensed production appears to be CFIC's most practical approach to this high volume market. CFIC plans to explore the US market for biomass and LP-fired TARGET systems to provide both hot water (for heat and washing) and electrical power at remote sites. U.S. commercialization could be launched in parallel with European cogen HVAC commercialization.

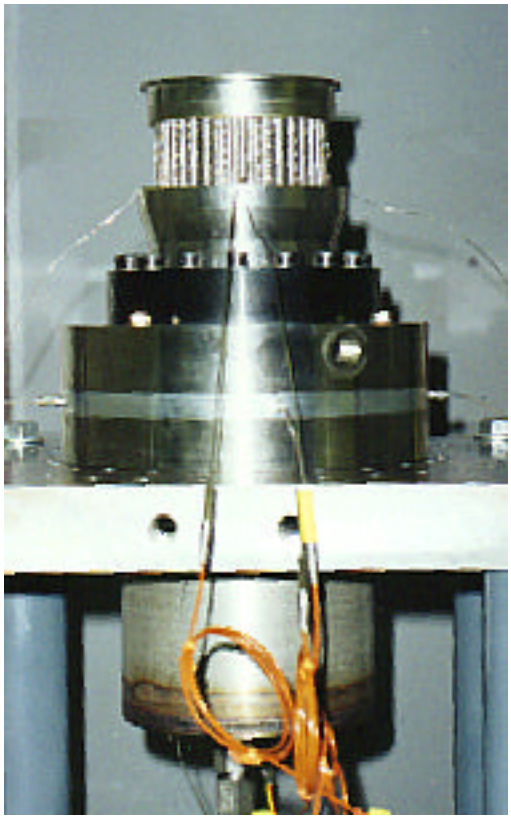


Figure 3: TARGET™ 500 watt Gas-fired Co-generator in Lab Stand 1998

3.2 Solar Electrical Generation

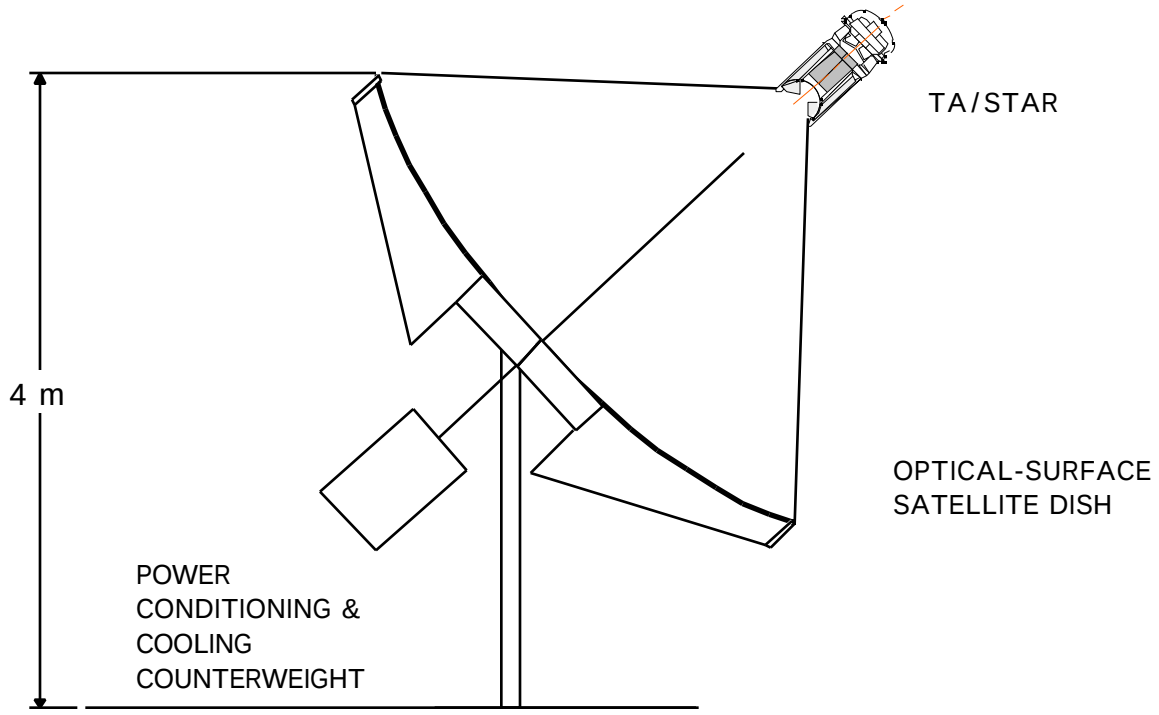
As a follow-on to the Cummins/DOE solar project, CFIC believes the significant cost savings and reliability enhancement of replacing the free-piston Stirling engine (FPSE) with a TAC driver for the STAR alternator will allow successful entry into the existing 1-3 kilowatt (kW) solar generator market. US distributors of Photo Voltaic (PV) systems are currently selling 1000-2000 PV systems in this size class per year for remote, off-grid housing and business needs. A 2 kW PV unit (without load storage and power management) retails for $14-16,000, plus installation. The current international market for PV systems is significantly larger than the US market.

Discussions with one of the leading satellite dish antenna manufacturers provided the estimated cost breakdown for a 2 kW net output (20% solar conversion efficiency) unit at a production rate of 1000 units per year:

· 14 ft. diameter dish structure, can support 200 lb. TAC/STAR package		$1500
· reflector surface		750
· tracker/mount control		500
· TAC driver		1500
· STAR alternator		2000
· hot water system		600
· power controls		1000
	Total	$7850

Using results from NYSERDA's feasibility evaluation testing and component design effort (see Section 3.1) and R&D funding from NREL and NYSERDA, CFIC plans to produce a 2 kW solar dish system prototype and initiate bench and on-sun TARGET testing in 1999. Sandia National Laboratories has committed to participate in and support on-sun prototype testing. Assuming full-commercialization program start in late1999, initial market ready 2 kW units could be available by mid-2001.

The most critical product development challenges are: (1) meeting at least 20,000 hour life with at least 20% solar conversion efficiency; and (2) producing a cost effective concentrator system.



4. STAR Driver For Oil-Free Compression and Vacuum Pumps

STAR motors, coupled with proprietary CFIC valving and control systems, offer significant performance enhancement and cost reduction benefits for oil-free air/gas compressors, vacuum pumps and vapor compression systems (as for air conditioning and heat pumping). CFIC has been working with two industry leaders (Single-Screw Compressors, Inc. and Australia's Cash Engineering) to define STAR application requirements. Already, special-purpose two-stage units using two STAR drives have been ordered by the National Institute for Standards and Technology (NIST) and the National Radio Astronomy Observatory (NRAO). These machines provide ultra-clean high compression in small, low-noise, low vibration, non-wearing packages.

The absence of rubbing wear in the STAR allows totally lubricant-free, long life operation. The compact, simple STAR package is considerably smaller (up to 50%) and cheaper than existing oil-free systems. The unique valving and control system maintains very tight clearance volume in the compression spaces (even with modulated stroke). The combination of high efficiency in the direct STAR drive and more complete use of the available compression space can produce more than 20% better efficiency and pressure range than existing rotary-driven reciprocating units in the 1-10 kW power class.

CFIC built a breadboard air compressor unit to verify fundamental performance and control modulation concepts. In addition, the NIST compressor has been completed and tested at design performance:14 litre/minute (nitrogen) from 1 to 28 bar pressure. CFIC plans to design a 2 kW, 2 stage demonstrator air compressor that will produce 6 cfm at 100 psi. CFIC believes a viable market channel is through OEMs, using a combination of licensing and sales of CFIC-built units. Market potential for this STAR package is very difficult to evaluate at this early stage of development, but if 10% of the total world-wide market for air compressors, vacuum pumps and vapor-compression systems in the 1-10 kW class had special needs that could be provided by the STAR, this would be a potential niche ultimately worth a few hundred thousand units per year.

Commercialization of the STAR compressor package is expected to take 18 months after full development is launched. The most critical development challenges are expected to be meeting the system efficiency and performance goals (at least 20% improvement over competing systems) and reducing the medium-volume (10,000 units per year) production cost to $1500 per unit.

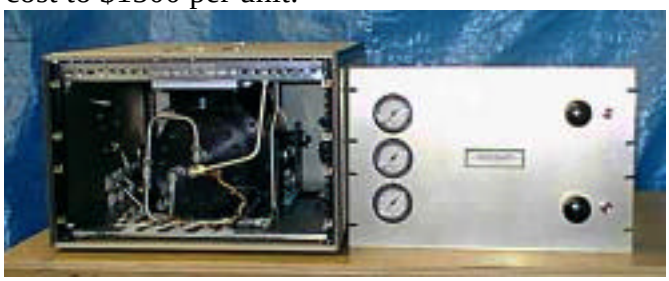


Figure 5: NIST 28:1 Two-stage Oil-free STAR-drive Nitrogen Compressor

5. Key Principals

John Corey: Most of his career has been devoted to the development of resonant energy systems, primarily using the Stirling engine cycle. He has designed and participated in the construction and testing of high performance heat exchangers for Stirling engines in the 1 to 60 kW range; refrigeration compressors, pressure vessels, and heat exchangers for gas-fired heat pumps; and numerous drive systems and auxiliary devices. More than two dozen U.S. and foreign patents have resulted from this work. During eight years as the Senior Design Engineer at MTI, Inc. (Latham, NY) he led a design team creating prototype Stirling engine cycles for heat pumps, automotive power and generator sets. He also invented a hydraulically-coupled hermetic refrigerant compressor. He founded CFIC, Inc. in 1989, originally to offer contract machine design services for manufacturing companies, primarily focusing on high speed material handling and advanced textile converting. He has since led the push for lubricant free-resonant conversion machinery development at CFIC.

- **Jay Browne:** For 27 years he held a variety of positions in marketing, sales, product development, operations and general management for GE's Aircraft Engines and Power Systems businesses. His extensive international experience includes creating new Joint Ventures, alliances and distribution channels in Europe and Asia, and living in Tokyo for 4 years. He has developed and manufactured numerous advanced mechanical and electro-mechanical components. Selected as one of GE's Total Quality Management initiative leaders, he also led ISO 9000 certification for a multi-plant engineering and manufacturing operation.

6. Summary

CFIC has identified several markets (including small scale combined heat and power and solar electrical) where the benefits of both the STAR alternator and the ThermoAcoustic Converter (TAC) technologies can be combined into the TARGET electrical power generation package. Additional markets (gas liquefaction, cryogenic cooling, non-CFC refrigeration and oil-free compression) appear to hold significant promise for the STAR linear motor.

CFIC's main strategy is to join forces with OEMs in these markets, thus providing fully funded commercialization programs for specific product applications and a common, mature technology base that can serve multiple market needs. Future CFIC revenues will be generated by a combination of low-rate production sales and license fees.